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A process-based model to derive methane emissions from natural wetlands

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Abstract. A process-based model has been developed in order to calculate methane emissions from natural wetlands as a function of the hydrologic and thermal conditions in the soil. The considered processes in the model are methane production, methane consumption and transport of methane by diffusion, ebullition and through plants. The model has been tested against data from a three-year field study from a Michigan peatland. The interannual and seasonal variations of the modelled methane emissions and methane concentration profiles are in good agreement with the observations. During the growing season the main emission pathway proceeds through plants. Ebullition occurs whenever the water table is above the soil surface, while diffusion is only significant in the first 15 days after a drop of the water table below the peat surface.

Introduction

Natural wetlands account for about 20% of the global methane emissions at present and are the major non-anthropogenic methane source [IPCC, 1994]. Emissions of methane from natural wetlands are a result of biological and physical processes taking place in the soil: methane production by methanogenic bacteria under anaerobic conditions, methane oxidation by methanotrophic bacteria under aerobic conditions and transport of methane through the soil to the atmosphere. All processes leading to methane emissions are controlled by physical, chemical and environmental parameters, such as height of the water table, soil temperature, organic matter content and plant species [Conrad, 1989]. Empirical relationships based on correlations between methane emissions and soil temperature and/or water table have been reported in several studies [e.g. Christensen et al., 1995; Dise et al., 1993; Whalen and Reeburgh, 1992]. The effect of vegetation on methane emission is demonstrated by the observed correlations between methane emissions and plant biomass or the Net Ecosystem Production [e.g. Whiting and Chanton, 1992]. However, such relationships typically explain only a fraction of the observed variance of the methane emissions and studies from various experimental field sites yielded vastly different results. Therefore, a more process based approach is needed to describe the functional relationship between emissions of methane and environmental parameters. The most important factors that influence methane emissions are:

(i) The position of the water table - separates anaerobic and aerobic conditions within the soil and thus defines the depth of the production and consumption zones, respectively.

(ii) Soil temperature - controls the rates of methanogenesis, whereas the effect of soil temperature on methane oxidation rates is small [Dunfield et al., 1993].

(iii) Plant communities - affect methane emissions at least in three ways: 1. easily decomposable organic matter is added to the soil through the release of exudates, dead fine roots and litter, 2. several plants in wetlands have been found to transport methane through their stems up to the atmosphere and 3. gas conducting plants transport atmospheric oxygen down to the roots which makes rhizospheric oxidation possible [Schütz et al., 1991; Holzapfel-Pschorn et al., 1986].

(iv) Transport - determines the amount of methane which reaches the atmosphere. It proceeds by three different mechanisms: molecular diffusion, ebullition and transport mediated by plants. Ebullition leads to a faster transfer of methane through the water saturated region than diffusion. Plant-mediated transport bypasses the aerobic soil zone of methane consumption and hence leads to enhanced methane emissions, if the water table is below the peat surface.

In order to investigate the response of methane emissions from natural wetlands to climatic changes, i.e. to altered thermal and hydrologic conditions in the soil, a 1-dimensional model has been developed which includes an explicit description of these processes. In the remainder of this paper we present a description of the model structure and its basic assumptions followed by an application to model observed emissions of methane from a peat bog in southern Michigan [Shannon and White, 1994].

Model Description

The 1-dimensional model describes formation, oxidation and transport of methane in a vertical soil column as shown schematically in Fig 1. Production of methane is confined to the region between the water table, w, and the bottom of the active soil zone, l, whereas oxidation occurs in the soil region above the water table. The active soil zone, which is the region where suitable substrate for methanogenesis is available, is assumed to coincide with the root zone. Numerically, the soil column is divided into parallel layers of 1 cm thickness. Three different transport mechanisms are modelled explicitly:

1. molecular diffusion through the soil pore space and the standing water, if the water table is above the soil surface,
2. transport by ebullition from the depth where bubbles are formed up to the water table and
3. transport through plants during growing season from the soil region above the rooting depth directly to the atmosphere.

As input data the model requires daily records of the position of the water table and the vertical profile of soil temperature. The model calculates methane concentration profiles in the soil and methane emissions to the atmosphere on a daily basis by numerically solving the 1-dimensional continuity equation within the entire soil/water column:

$$\begin{aligned} \frac{\partial}{\partial t} \cdot C_{CH_4}(t,z) &= -\frac{\partial}{\partial z} \cdot F_{diff}(t,z) \\ &+ Q_{ebull}(t,z) + Q_{plant}(t,z) \\ &+ R_{prod}(t,z) + R_{oxid}(t,z) \qquad (1) \end{aligned}$$

where C_{CH_4}(t,z) is the methane concentration at time t and depth z, F_{diff}(t,z) the diffusive flux of methane through the

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soil, $Q_{ebull}(t,z)$ and $Q_{plant}(t,z)$ represent sinks due to ebullition and plant-mediated transport, respectively. $R_{prod}(t,z)$ is the methane production rate, while $R_{oxid}(t,z)$ denotes the methane oxidation rate.

The diffusive flux $F_{diff}(t,z)$ is calculated using Fick's first law. The diffusion coefficient is specified from Penman's relation [Hillel, 1982], whereas the soil pore space relevant to diffusion is assumed to be equivalent to the volume of the coarse pores (diameter $\geq 10\ \mu m$). The diffusion coefficient in the saturated zone is set to be 10^{-4} times the diffusion coefficient in the unsaturated zone [Scheffer and Schachtschabel, 1984].

Similar to the assumption given by Rothfuss [1994], bubble formation occurs, if the sum of the partial pressures of all gases in the pore water exceeds a threshold value which is the sum of the hydrostatic and the atmospheric pressures plus the pressure required to move the soil particles. In the model, bubbles are formed if the methane concentration in the pore water becomes greater than a threshold value C_{max} of $500 \mu M$, being equivalent to a partial pressure of 260 matm at $10^{o}C$ or a mixing ratio of 25% methane in the bubble. It is assumed that the remaining gas in the bubble is mainly nitrogen [Chanton and Dacey, 1991; Shannon et al., 1996]. The rate $Q_{ebull}(t,z)$ at which methane in the form of bubbles is removed at time t from depth z is calculated from:

$$Q_{ebull}(t,z) = -k_e \cdot f(C_{CH_4}) \cdot (C_{CH_4}(t,z) - C_{max}) \qquad (2)$$

where k_e is a rate constant (h^{-1}), $f(C_{CH_4})$ is a step function taking the value 1, if $C_{CH_4}(t,z)$ is greater than C_{max} and 0 otherwise. A fraction A_{por} (=70%) of bubbles is transported instantaneously up to the water table, while the remaining bubbles are assumed to be trapped in the upper part of the water saturated soil layers until the water table drops below the depth where they are located in or until the pore space filled by gas bubbles exceeds 30%. Hence the bubble flux $F_{ebull}(t)$ is obtained by:

$$F_{ebull}(t) = \int_{l}^{w} A_{por} \cdot Q_{ebull}(t,z) \cdot dz \qquad (3)$$

During the growing season methane from layers above the rooting depth is also transported through plants to the atmosphere. Gas transport through plants is known to operate by molecular diffusion, effusion or active transport due to pressure differences [Schütz et al., 1991; Whiting and Chanton, 1992]. The results from several studies suggest that the main emission pathway is by molecular diffusion or effusion [e. g. Nouchi and Mariko, 1993; Chanton et al., 1992, Shannon et al., 1996]. Nouchi and Mariko [1993] found a linear relationship between methane emission rates through plants and methane concentrations in the pore water. Here, the rate $Q_{plant}(t,z)$ at which methane is removed from depth z at time t by plants is calculated from:

$$\begin{aligned} Q_{plant}(t,z) \; &= \; -k_p \cdot D_{veg} \cdot T_{veg} \\ &\quad \cdot f_{grow}(t) \cdot f_{root}(z) \cdot C_{CH_4}(t,z) \end{aligned} \qquad (4)$$

where k_p is a rate constant (h^{-1}), D_{veg} a factor describing the density of plant stands and T_{veg} a measure for the gas conducting properties of the dominant vegetation type. Here D_{veg} has been set to 0.5 while T_{veg} was left as an adjustable parameter. The function $f_{grow}(t)$ describes the growing state of the plants. Here it is assumed to be a function which is constant during winter time and increases linearly from the time the plants emerge from the peat until maturity, followed by a linear decrease until most of the plant stems are killed by frost. The function $f_{root}(z)$ describes the vertical root

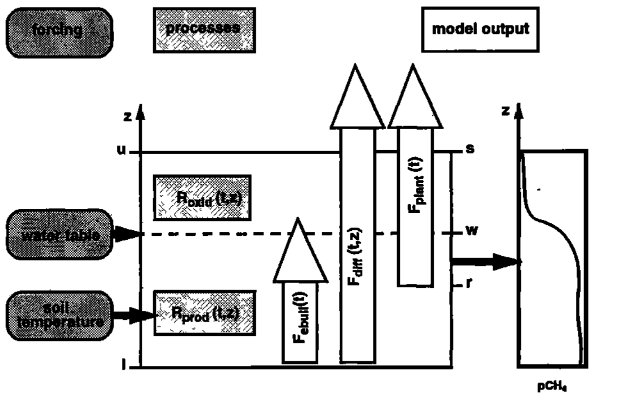

Figure 1. Schematic representation of the model structure: l is the lower boundary of the 'active region', while u denotes the upper boundary which is either the soil surface s or the water table w. The forcing consists of daily records of the water table and the soil temperature. The position of the water table divides the soil into the anaerobic region (l<z<w), where methane production (R_{prod}) occurs and the aerobic region (s>z>w), where methane is oxidized (R_{oxid}), while the soil temperature affects the methane production rate R_{prod}. The considered transport processes (thick arrows) are ebullition (F_{ebull}), which occurs in the water saturated region, diffusion (F_{diff}) through the soil pore space and the standing water, if w>s, and transport through plants (F_{plant}) from the soil layers above the rooting depth r. The model output is the rate of methane emission to the atmosphere and the methane concentration profile in the soil, calculated on a daily basis.

distribution: it is zero below the prescribed rooting depth and increases linearly upwards, which is an approximation of the average vertical root distribution patterns presented in Jackson et al. [1996]. Since gas conducting plants are capable of transporting atmospheric oxygen down to the roots, a fraction P_{ox} (in the model set to 50%) of methane is reoxidized in the rhizosphere [Schütz et al., 1989; Gerard and Chanton, 1993]. Thus, the plant flux $F_{plant}(t)$ is calculated from:

$$F_{plant}(t) = \int_{r}^{s} (1 - P_{ox}) \cdot Q_{plant}(t,z) \cdot dz \qquad (5)$$

where r denotes the rooting depth. Methane production rates depend mainly on substrate availability and quality, and increase with increasing temperature [Valentine et al., 1994; Conrad, 1989]. Here we describe the production rate $R_{prod}(t,z)$ as follows:

$$R_{prod}(t,z) = R_0 \cdot f_{org}(z) \cdot f_{in}(t) \cdot Q_{10}^{\frac{T(t,z)}{10}} \cdot f(T) \qquad (6)$$

where R_0 is a constant rate factor, which is a measure for substrate availability and quality and was left as a second adjustable model parameter. The function $f_{org}(z)$ describes the vertical distribution of substrate for methanogenesis within the soil profile. At vegetated sites it is assumed to be constant with depth due to the input of easily decomposable organic matter by roots. The prescribed function $f_{in}(t)$ describes the input of easily decomposable organic matter into the soil. Here it is specified to be proportional to the monthly Net Primary Productivity [Knorr and Heimann, 1995], supplemented by a secondary peak in autumn caused by dying plants and roots. The Q_{10} value describing the temperature dependency of formation of substrate for methanogenesis and methane production, was choosen to be 6, lying within the range of observed Q_{10} values for methane production [Dunfield et al., 1993; Westermann, 1993]. The step function f(T) is 0, if T(t,z) is less than 0°C, and 1 otherwise, assuming that there is no methane production at temperatures below 0°C.

Oxidation of methane by methanotrophic bacteria in the aerobic soil region follows Michaelis-Menten kinetics [Bender and Conrad, 1992], described by:

$$R_{oxid}(t,z) = -\frac{V_{max} \cdot C_{CH_4}(t,z)}{K_m + C_{CH_4}(t,z)} \quad (7)$$

where K_m and V_{max} are the Michaelis-Menten coefficients, choosen to be 5μM and 30μM/h, respectively [Dunfield et al., 1993].

The total methane emissions $F_{tot}(t)$ are given by the sum of the diffusive flux $F_{diff}(t,z{=}u)$ at the soil/water - atmosphere boundary u, the bubble flux $F_{ebull}(t)$ and the plant flux $F_{plant}(t)$:

$$F_{tot}(t) = F_{diff}(t, z = u) + F_{ebull}(t) + F_{plant}(t) \quad (8)$$

Results and Discussion

The model was evaluated against observations of a three-year field study by Shannon and White [1994] from an ombrotrophic peatland in southern Michigan, called Buck Hollow Bog. During this study measurements of methane emissions were conducted at 10 to 14 day intervals while concentration profiles were obtained once to twice per month. In addition, water table and soil temperature were observed on a weekly to daily basis. The roots of the dominant vascular plant *Scheuchzeria palustris*, which was found to emit significant amounts of methane, penetrated about 50-80 cm below the peat surface. The porosity of the soil was 90% to 95% and the organic carbon content was 50%.

The model was run forced by water table and soil temperature data which had been linearly interpolated to a daily basis (Fig. 2c,d). The comparison between the modelled methane emissions and the data is displayed in Fig. 2a. The agreement between the modelled methane emissions and the data is good: the modelled interannual and seasonal variations in methane fluxes correspond well with the data and calculated fluxes lie within ± 1SD of the data in most cases. The choice of the two adjustable parameters, R_0 and T_{veg}, which were determined by simultaneously fitting both, the overall magnitudes of the modelled methane emissions and the methane concentration profiles, does not affect the temporal pattern in the modelled methane emissions and concentration profiles.

Modelled emissions in 1991 were higher than in 1992 and 1993, which were caused by slightly higher soil temperatures in 1991 (Fig. 2d). At times when the water table was above the soil surface, the pattern of methane emissions was dominated by changes in the soil temperature. The effect of the water table falling below the peat surface on methane emissions can be recognized in the summer of 1991: methane emissions declined to values below 200 mg/m^2·d already in August, even though the soil temperature was still high at that time, while in 1992 and 1993 the drop to values around 200 mg/m^2·d occured much later in October. Fig. 2b shows the contribution of the three different transport mechanisms to total methane emissions. During the growing season the main emission pathway is through plants which is in good agreement with the measurements: emission of methane through *Scheuchzeria palustris* was observed in plant enclosure experiments and estimated to account for 64-90% of the net methane flux [Shannon and White, 1996].

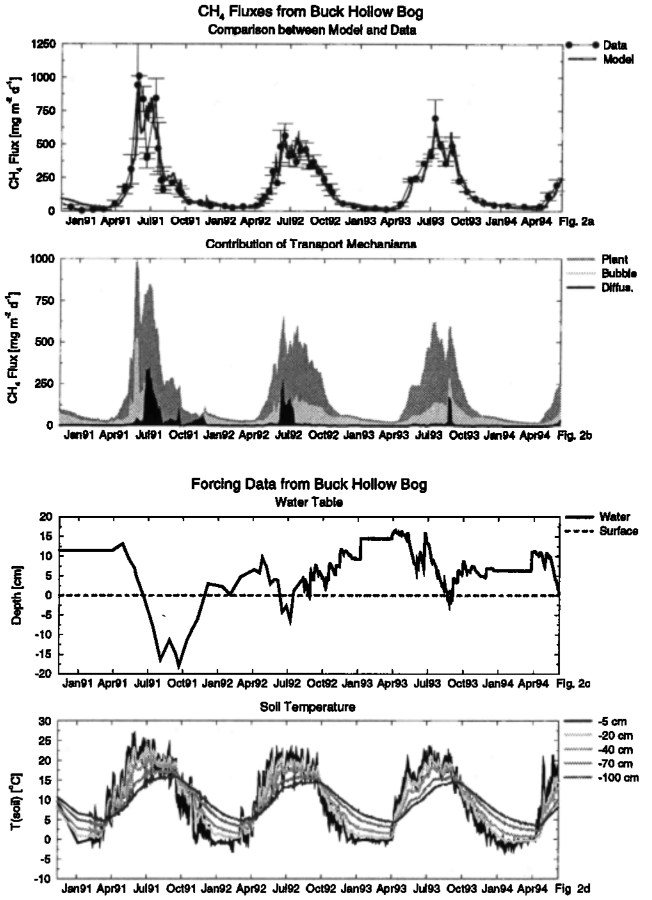

Figure 2. a. Comparison between modelled (thick line) and measured (dots with ± 1SD error bars) methane emissions, **b.** Contribution of the three transport mechanisms: diffusion (black), ebullition (light grey) and plant-mediated transport (dark grey), **c.** Water table position, **d.** Soil temperature at different depths below the peat surface.

In periods when the water table is above the soil surface, transport by diffusion is insignificant because of the small diffusion coefficient of methane in water. In June 1991 it can be seen how the respective contributions of the different emission pathways change if the water table falls below the peat surface: emission by ebullition stops as the water table drops below the soil surface while emission by diffusion increases almost instantaneously because of three reasons: 1. the diffusion coefficient increases by a factor of 10^4 as soon as the soil becomes unsaturated, 2. shortly after the water table drops below the peat surface methane concentrations in the zone directly below the surface are still high and 3. methane, which was trapped in the form of bubbles in the upper soil layers, is released. After about 15 days, emission by diffusion declines again, due to oxidation in the unsaturated zone. Moore and Roulet [1993] observed a similar pattern: increased fluxes with falling water table to 20 cm depth within 10 days, followed by decreased fluxes as the water table continues to fall. The amount of methane released through plants decreases soon after the water table falls below the peat surface, because less roots extend to depths with water saturated soil, where high methane concentrations prevail.

The comparison between modelled and measured methane concentration profiles in the soil is shown in Fig. 3 for the period between July 1992 and January 1993. The simulated seasonal changes are in good agreement with the

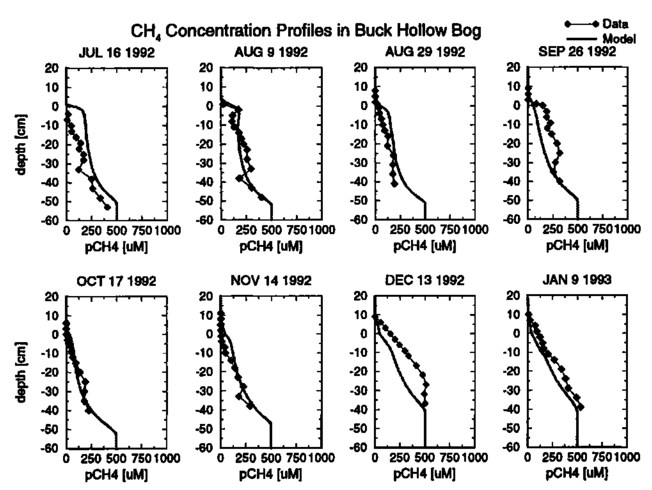

Figure 3. Methane concentration profiles in the soil: Comparison between model results (thick lines) and observations (squares).

observations. Methane concentrations in the soil are higher during winter time than during summer time, even though methane production rates are higher in summer due to higher soil temperatures. This is an effect of transport: during the growing season large amounts of methane are removed from the soil by plants. During winter, plant-mediated transport is greatly reduced by senescence of emergent plants. Therefore, methane accumulates in the soil since diffusion through water saturated soil is slow and bubble formation starts when the methane concentration of pore water exceeds 500μM.

Because of limited information, the choice of the following additional model parameters has some uncertainties: the fraction of methane being reoxidized in the rhizosphere P_{ox} has been choosen to be 0.5 over the whole season although it may increase with increasing maturity of the plants [Schütz et al., 1989; Gerard and Chanton, 1993]. The fraction of bubbles trapped within the soil has been set to 0.3, which, given the lack of knowledge concerning the behaviour of gas bubbles in soils, represents an educated guess. However, the values of these parameters had little effect on the model results. To apply the model to other sites and under different climatic conditions the parameters T_{veg} and D_{veg} will be empirically determined from data sets/maps of the predominant vegetation class and the density of plant stands. Since R_0 is a measure for substrate availability and quality we assume that it can be determined as a function of the plant biomass or the NPP.

Conclusion

The results of this study show that methane emissions and methane concentration profiles can be simulated under different hydrologic and thermal soil conditions using the process based model described above. The seasonal pattern in methane emissions as well as in the methane concentration profiles in the soil is significantly affected by the position of the water table, by changes in soil temperature and by the various transport mechanisms. Data sets from other wetlands covering a period of at least one year are needed to further validate the model. To reduce the model uncertainties further investigation of the processes involved in methane emission will be necessary.

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